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PROTOCOL AND DEMONSTRATIONS OF PROBABILISTIC RELIABILITY ASSESSMENT FOR STRUCTURAL HEALTH MONITORING SYSTEMS (PREPRINT)

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14. ABSTRACT
This paper will describe the development of a protocol for probabilistic reliability assessment for SHM systems as well as present an experimental demonstration for a vibration-based structural damage sensing system. The results of the full validation study highlight the general protocol feasibility, emphasize the importance of evaluating key application characteristics prior to the POD study, and demonstrate an approach to quantify varying sensor durability on the POD performance. Challenges remain to properly address long time-scale effects with accelerated testing and large testing requirements due to the independence of the inspection of the inspection of each flaw location.

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Protocol and Demonstrations of Probabilistic Reliability Assessment for Structural Health Monitoring Systems

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Abstract
This paper will describe the development of a protocol for probabilistic reliability assessment for SHM systems as well as present an experimental demonstration for a vibration-based structural damage sensing system. The results of the full validation study highlight the general protocol feasibility, emphasize the importance of evaluating key application characteristics prior to the POD study, and demonstrate an approach to quantify varying sensor durability on the POD performance. Challenges remain to properly address long time-scale effects with accelerated testing and large testing requirements due to the independence of the inspection of each flaw location.

Keywords: Model-assisted POD evaluation, probability of detection (POD), reliability, structural health monitoring

1. Introduction

The successful deployment of systems for health monitoring of structures depends on appropriate verification and validation (V&V) of these structural health monitoring (SHM) systems. The V&V method must explicitly evaluate all aspects of the SHM system that can affect its capability to detect, localize, or characterize damage. Moreover, it must evaluate the effects that usage and environmental conditions have on these capabilities over time. The current U.S. Air Force practice for maintaining aircraft structures follows the Aircraft Structural Integrity Program (ASIP) methods, as documented in MIL-STD-1530C [1]. A critical part of the damage tolerance approach is the assessment of the reliability of Nondestructive Evaluation (NDE) methods that are used for the periodic inspection of structures. MIL-HDBK-1823A provides guidance on probabilistic methods for NDE reliability assessment and introduces the use of models to complement experimentation for a probability of detection (POD) determination [2]. As SHM methods depending on permanent, on-board mounted damage sensing systems continue to be proposed and developed for complementing ground-based NDE inspections for aircraft structural integrity purposes, it is necessary that the reliability of these damage sensing systems be assessed with a rigor that is suitable and sufficient for the function that they are expected to perform within the ASIP methodology [3]. For damage detection, this necessarily results in the need for a POD determination. For localization and characterization, the metrics and their evaluation process are the subject of current research and development [4]. This paper will present a demonstration of the damage detection protocol utilizing empirical data, models, and uncertainty analyses for characterizing SHM reliability [5].

2. Protocol

An outline of the MAPRA protocol is given in Figure 1. The MIL HDBK 1823A for USAF NDE certification based on POD is the foundation of the protocol [2]. In addition, model-assisted approaches must be applied to address limits of experimentation, facilitate proper uncertainty analysis for damage detection cases and expand the assessment to quality of localization/characterization estimates. This protocol includes four critical components: (1) a procedure to identify the critical factors impacting SHM system performance; (2) a multistage or hierarchical approach to SHM system validation; (3) a model-assisted evaluation process to address the wide range of expected damage conditions that cannot be experimentally tested; and (4) POD, probability of false call (POFC) and probability of random missed call (POMC) evaluations with confidence bounds estimation and uncertainty analysis for damage detection SHM systems, and evaluation of appropriate probabilistic metrics to characterize the quality of damage localization and damage characterization for SHM systems that include such capabilities. The multistage validation approach is designed to incrementally test SHM systems with structures of increasing complexity. The multistage approach includes (a) laboratory testing of relevant flaws, (b) laboratory sub-component testing including environmental and loading conditions, (c) a system level life-testing (full-scale fatigue testing if feasible), (d) on-structure demonstration, and (e) final system verification.

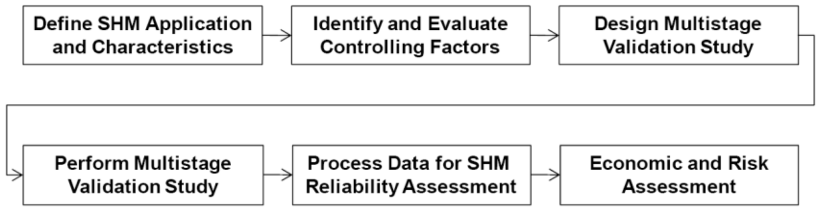

Figure 1. Outline of protocol for SHM validation.

A model-assisted strategy for the design and execution of POD studies for NDE has been developed and demonstrated to help mitigate validation costs and to improve POD evaluation quality by addressing a wider array of inspection variables. By including greater sophistication in the models, there should be less error present between the model and available experimental data. By addressing variability in the model and minimizing unexplained error in the representation, less experimental data will be required to address the unknowns in the evaluation. The following opportunities in the POD model evaluation and application steps have the potential to impact sample and testing requirements: (a) careful *model factor selection* addressing system variation, (b) *physics-based model calibration* including uncertainty bounds assessment for the specific inspections of interest, (c) controlled *physics-based model validation* to ensure the model is valid over desired range of application, (d) *evaluation of POD using two-level analysis* to address input *parameter variability with uncertainty bounds*, (e) *integration of experimental data* generated from a *designed experiment* using a *Bayesian framework* to revise the prior distributions of inputs and achieve new posterior distributions, and (f) *inverse methods* to ideally address all uncontrolled parameter variations in the measurement. More information on the protocol can be found in reference [5].

3. Experimental Study Setup

The example used for this initial demonstration of the protocol is a system for detecting the presence of damage using permanently mounted transducers. A test article representing an aircraft structure of medium complexity was designed and built. The test article consists of three plates connected by two lap joints with fasteners (see Figure 2). In addition, a fixture was built for supporting the test article. Fatigue crack damage around the fastener holes can be simulated by manually created thin cuts at selected locations. The test fixture design provides the capability to vary critical parameters of the system with a focus on force loading boundary conditions, joint fastener torque conditions, and temperature.

The initial demonstration on this test article and fixture uses a vibration based damage detection method. An ETrema brand Terfenol-D magnetostrictive actuator was used for band-limited pseudo-random excitation up to 1200 Hz, and the dynamic response of the plate was recorded using eight 50mV/g single-axis accelerometers set to measure out-of-plane motion and provide input to change detection algorithms. The accelerometers were placed at locations that attempt to maximize the ability to detect change in the modal dynamics of the structure even in the presence of modeling errors. M-Bond 200 adhesive was used for semi-permanently affixing the accelerometers to the bottom of the assembly. Four bonded foil 350-ohm strain gages were also installed on the test article for tracking the state of stress under mechanical loading. Finally, thermocouples were also used for studying the effects of heating due to excitation of the damage detection system and the effects of the operational temperature. The layout of the sensors is presented in Figure 2. A LabVIEW data acquisition system was used for acquiring the required data. Variations in operational temperature were simulated by testing the system inside a carefully controlled Thermotron SE-1200 environmental chamber.

The method for inducing damage involved notching the area of the „skin"under a fastener. To initially isolate damage to the skin alone, the test article design includes machined relief slots in the joining plate at the fastener locations. A change metric based on the area under the curve representing the difference between two frequency responses from 200 to 1200 Hz and an R-square metric were used for assessing changes in structural dynamics due to mechanical and thermal loading, actual damage, and combinations thereof, and therefore attempting to detect damage presence and growth.

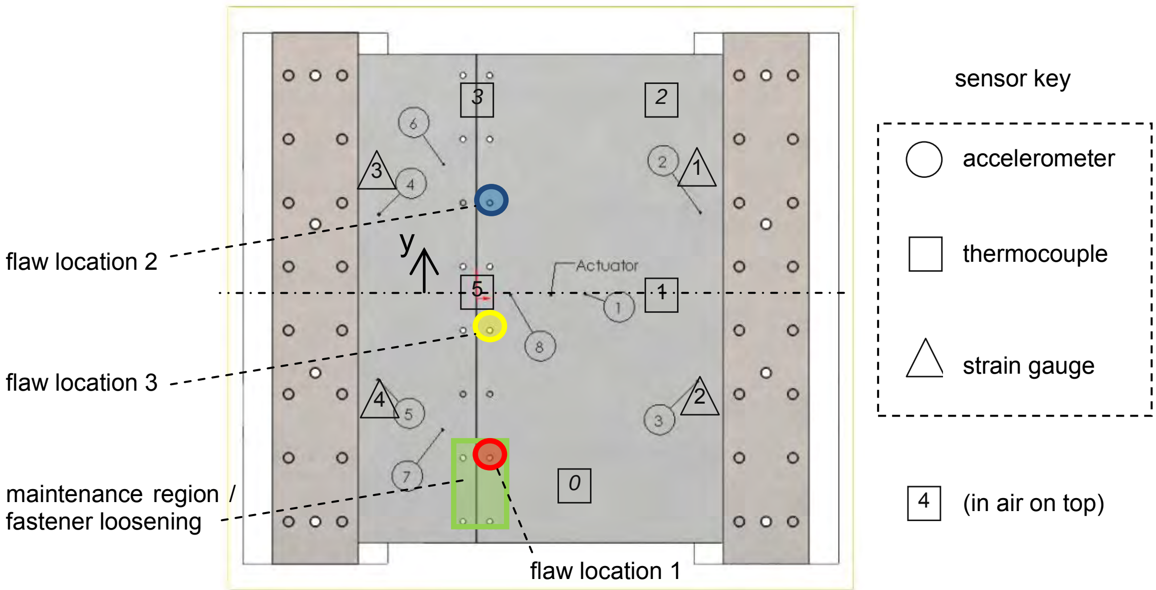

Figure 2. Location of sensors on the test article.

4. Factor Evaluation Studies

Following the protocol, prior to designing the validation study test matrix, the following factors were assessed through controlled studies: (a) mass loading and unloading, (b) fastener torque, (c) boundary condition variation, (d) temperature variation and temperature gradients, (e) sensor bond quality, (f) ambient noise, and (g) flaw growth. More details on the factor evaluation studies are presented in reference [6].

Thermal loading studies were performed by varying the ambient temperature from -20°F to 150°F. During this study, the thermal capacity of the panel end conditions fixtures was found to produce significant thermal gradients across the test article. During heating and cooling periods, temperature gradients as high as 45°F across the test specimen were observed. For validation studies, an estimate of expected gradients „in the field" is needed. An assumption was made for the validation study that temperature gradients in the region of interest will be primarily limited to +/- 10°F.

To address the temperature conditions, a new temperature compensation algorithm was designed and implemented that (1) uses multiple FRF references at different temperature bands and (2) incorporates a nonlinear frequency shift model for local temperature compensation. An approach was tested that uses three baselines, one at the nominal temperature, one at a higher temperature range (with minimal temperature gradients) and one at the low temperature range. The algorithm then evaluates the minimum of the three damage metric results. A two parameter frequency shift model was introduced

$$f_{new}(f) = f + \left(\frac{\phi_1}{1000\,\text{Hz}}\right) f + \phi_0, \tag{1}$$

where ϕ_0 and ϕ_1 represent bias and slope adjustments, respectively. A nonlinear least squares estimation routine was implemented to evaluate ϕ_0 and ϕ_1 and a log transform of the FRFs was used to enable sensitivity to changes all along the FRF, not just at the peaks. Through the use of this temperature compensation algorithm, significant improvements to the damage metric were achieved. One downside with the algorithm is that the fit and interpolation process take longer (seconds) to run. As well, there is still some difficulty in compensating for rapid temperature changes that produce severe gradients across the plate.

Failure of accelerometer bonding was observed several times during factor thermal testing. These failures occurred during the prolonged high temperature runs at 150°F. Coherence was shown to be a viable metric to monitor bond quality over time. While vibration-based damage detection systems are proposed as global methods with some sensor redundancy, relying on a single reference sensor will result, upon bond degradation, in either highly degraded performance and/or complete failure of the damage detection system well before the structure end-of-life is reached. Sensor and sensor bonding reliability must therefore be accurately assessed as part of a validation study.

The noise generated by the environmental chamber and by other equipment in the laboratory posed an opportunity for studying the effects of ambient noise on the detection capability. Coherence levels were observed to change depending on whether the unit was cooling or heating and the „throttle" level of the chamber, and on whether the chamber door was open or closed. For the validation study, both „chamber on" and „chamber off" conditions will be acquired in order to include in the analysis the effects of varying noise conditions that are expected in the field.

An initial study on the effect of damage growth was performed to ensure adequate sensitivity during the final validation study. Customized XActo™ blades were used to make cuts in the aluminum plates. The resulting notch width was found to be 0.012" +/- 0.002". Cuts were initially made at 0.063" (1/16") increments up to 0.63". For the first series of cuts up to 0.25", sensitivity to notch length increases was observed, but the trend was small relative to noise, and not quite linear. Greater sensitivity to the larger cuts was observed and clear sensitivity to notches on the order of 0.63" was demonstrated. Note, a significant increase in the damage metric was observed after a two week delay between the end of the 0.25" notch cut and the start of the 0.31" notch cut. Relaxation of the boundary conditions over time was thought to be the source of the change. For validation, controlled time delays should be included into such studies to isolate and addre

5. Design of Validation Study

The validation study consisted of growing flaws by artificially cutting the structure at two fastener site locations, site 2 and site 3, as shown in Figure 2. A series of environmental and boundary conditions were studied after each flaw growth scenario: temperature variation (+/- 40°F), temperature gradients, loading and unloading of 10 lb mass, a simulated maintenance action at a set of fasteners (see Figure 2) including the case of minor loosening, and reinstallation and replacement of accelerometers. During the flaw growth period, tests were performed before and after flaw growth, and after fastener installation. Temperature chamber states of „on" and „off" with the ambient temperature set to T = 72°F were acquired for all test conditions. Five averages were taken for all SHM system acquisitions. After any environmental condition or change to the test fixture, testing was performed with the ambient temperature returned to T = 72°F.

6. POD Analysis Approach

A summary description of the approach being followed for obtaining a probability of detection model for on-board damage detection cases follows. Conventional probability of detection (POD) evaluation for many quantitative NDE applications first uses empirical data to evaluate statistical relationships between the measurement response, $\hat{a}$, and the primary flaw size variable, *a*. Through application of a detection criterion as part of the NDE procedure, this statistical „$\hat{a}$ versus a' model can be used for evaluating the POD curve and probability of false call (POFC) rate, which together are usually referred to as "a POD model". The detection system can be abstractly represented by a set of random variables a_i that act as inputs to a measurement model. Input variables can be categorized as being controlled (e.g. flaw size and material properties) or uncontrolled (e.g. liftoff, flaw morphology, and measurement noise). Detection consists of the measurement model output $\hat{a}$ being classified (or "called") according to pre-specified rules (e.g. a threshold).

The model-assisted POD (MAPOD) approach proposes to replace a conventional statistical fit in the measurement model with a complete physics-based model, *f*, calibrated for a given set of experimental conditions. This relationship is given by

$$\hat{a} = \beta_0 + \beta_1 f(a_i) + \varepsilon, \qquad (2)$$

where β_0 and β_1 represent the model calibration parameters, and ε represents the residual error between the model and the experimental data. Estimating the statistics of β_0, β_1, and ε necessitates specific experimental sampling requirements. Variations due to flaw size and environmental (noise) conditions, for example, are represented in the model as probability distributions of the input variables. Hybrid models incorporating both empirical and physics-based components can be implemented to address all key factors including those that cannot be adequately simulated. For this study, due to a lack of a validated physics-based model, a surrogate model fit using empirical data was applied in the evaluation.

In this study, the primary variable associated with the critical flaw size is crack (notch) length, a_1. Controlled secondary variables in the study include flaw location (a_2), mean temperature (a_3), temperature gradients (a_4), ambient noise level (a_5). A response surface methodology was applied here to estimate the effect of each factor on the damage metric response and construct a model, $f(a_i)$ including uncertainty. Random events such as sensor failure / disbond (b_1), sensor bond degradation (b_2), sensor replacement (b_3), and local maintenance actions (b_4) were considered in the POD evaluation study. Assumptions concerning their frequency can be made and empirical models representing their effect can be evaluated and applied in conjunction with the scope of the SHM application.

To complete the POD evaluation, an assessment of the detection model under varying input conditions including uncertainty propagation is necessary. In [10], a second-order probabilistic approach has been developed to propagate both aleatory uncertainty, due to inherent randomness in system behavior, and epistemic uncertainty, due to a lack of knowledge about values expected to be fixed. Using this approach, epistemic variables are specified as intervals on values of parameters such as the means and standard deviations of random variables. Monte Carlo analysis is applied here using outer and inner loops. The outer loop varies the values of distribution parameters of selected epistemic variables while the inner loop samples from the distributions. For this study, the distributions for the input variables, mean temperature and temperature gradients, are presented in Figure 3.

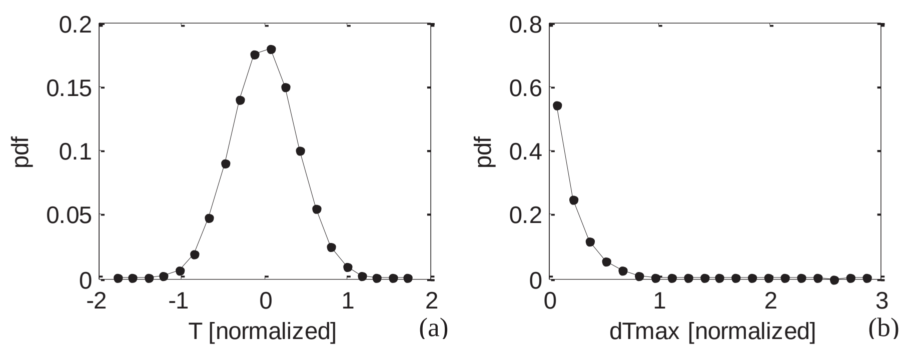

Figure 3. Distributions for temperature parameters: (a) mean normalized temperature (*T*), (b) maximum temperature gradient (*dTmax* / 10°F).

7. POD Evaluation Results

7.1 Sensitivity of POD to Flaw Location

Following acquisition of the experimental data, a regression model fit was performed to evaluate $f(a_i)$ using the R software environment. Three different flaw models were considered in the evaluation: (a) a flaw 2 and 3 combined evaluation (including flaw location factor, a_2), (b) a flaw 2 evaluation only, and (c) a flaw 3 evaluation only. One reason for performing and studying separate model fits for the different flaw growth sites was due to early observations that the SHM system was more sensitive to changes in flaw 3 with respect to changes in flaw 2. POD analysis results for the vibration-based SHM study are presented in Figure 4 with respect to flaw size (in inches) for the case of a damage call threshold of 0.05. The damage metric initially tested was based on taking the median response from all of the active frequency response functions (FRF), in order to minimize sensitivity to outlier sensor responses during operation. For each POD evaluation, both input parameter variation and model uncertainty are addressed through a two-level Monte Carlo simulation. To minimize simulation time, 2000 samples were used for each level, and the POD evaluation was performed at 51 different flaw sizes from 0.0 to 1.0 inch.

From these results, there is clear need to separately evaluate the POD models for flaw 2 and flaw 3 locations. A single POD curve does not properly address the poor detection capability at the flaw 2 location as a function of performance at large flaw size. Using the 'flaw 2 and 3 combined' results will give one a false sense of security in terms of detection capability. Note, for any future SHM validation study, care must be taken to ensure the 'overall' POD capability evaluations do not mask 'isolated' flaw locations that have poor detection capability. Likewise, the low false call rate in the flaw 3 model is likely due to the flaw 3 model only including a portion of the simulation study variation. In future work, the false call model should try to include all experimental study data. Lastly, POD results for flaw 2 shown in Figure 4(b) can be improved by using only the optimal sensor #6 data.

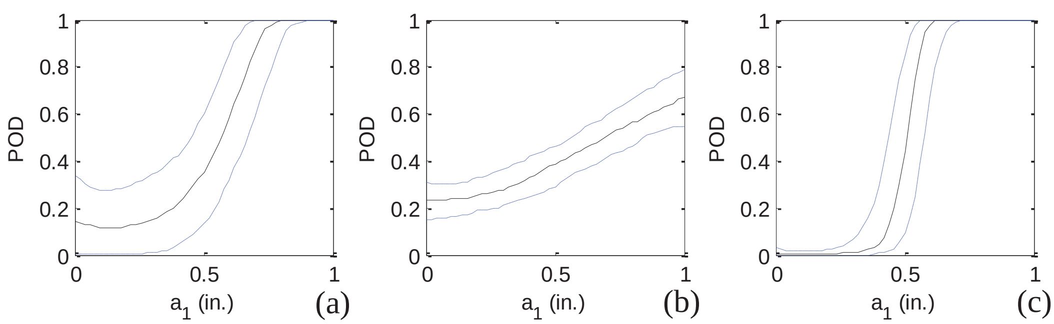

Figure 4. POD results with respect to flaw size including uncertainty bounds for (a) combined flaw 2 and 3, (b) flaw 2 only, and (c) flaw 3 only (*dm_threshold* = 0.05, use median sensor response).

7.2 Impact of Sensor Degradation over Time

This analysis approach enables the evaluation of the impact of sensor durability on POD performance. To perform this study, a strategy to address sensor durability issues must first be clearly defined upfront, as shown in Figure 5. Two sensor failure scenarios are of particular interest here: failure of the optimal detection sensor (accelerometer 6), and failure of the reference sensor. For the example of „flaw 3" results shown in Figure 5, it is clear how the corresponding POD curves are degraded with respect to the optimum case.

Next, models for sensor performance degradation (i.e. failure rates) are required for the evaluation. To represent the failure rate of in-situ sensors like strain gauges or accelerometers, a „bathtub" curve is often used [8]. It describes a particular form of a hazard function which comprises three parts: an initial decreasing failure rate, known as infant failures, a second part representing a constant failure rate, known as random failures, and a final part representing an increasing failure rate, known as wear-out or fatigue failures. Evidence from strain gauge sensor data on C-17 aircraft demonstrates the need for assessing the impact of degradation, where 22% of the sensors were infant failures and about 40% of the total failed within the first ten years of the aircraft life [9]. Given that only eight sensors are present in the subject SHM system, the scenario of 25% failures, two accelerometers, will be considered during the first 6 year period of operation. Figure 6(a) presents two probability density functions for the time to failure for the first and second sensors. Here, gamma distributions are applied to represent portions of the „bathtub" curve.

Data tables were constructed evaluating POD models for all of the „single sensor" and 'two sensor" failure scenarios. A Monte Carlo simulation was then performed using 10000 samples from the time to failure distributions for the first and second sensors. Equal probability of failure was assumed for the eight accelerometer locations. The POD(t) curve was evaluated at 0.1 year time increments for 6 years. Results are presented in Figure 6(b) for the mean value from the composite Monte Carlo simulation POD results at a flaw size of 1.0 inch as a function of time. Results for both flaw 2 and flaw 3 locations are presented. This analysis is useful because it highlights the sensitivity of certain flaw locations to degradation in the SHM system. In particular, the detection of flaw 2 suffers from weak crack sensitivity with respect to significant noise sensitivity due to varying temperature conditions. Flaw 3 detection capability was found to be quite robust to the failure of only one or two accelerometers.

8. Summary

This work has presented the results of a demonstration featuring the application of a proposed validation protocol to a vibration-based structural damage sensing system. The design and results of the full validation study highlight the general protocol feasibility, emphasize the importance of evaluating the key application characteristics prior to the POD study, and demonstrate an approach to quantify varying sensor durability on the POD performance. However, challenges remain, in particular on how to properly address long time-scale effects with accelerated testing and how to address large testing requirements given the independence of each flaw location in the evaluation. Going forward, by better leveraging validated numerical models, it may be feasible to address these challenges.

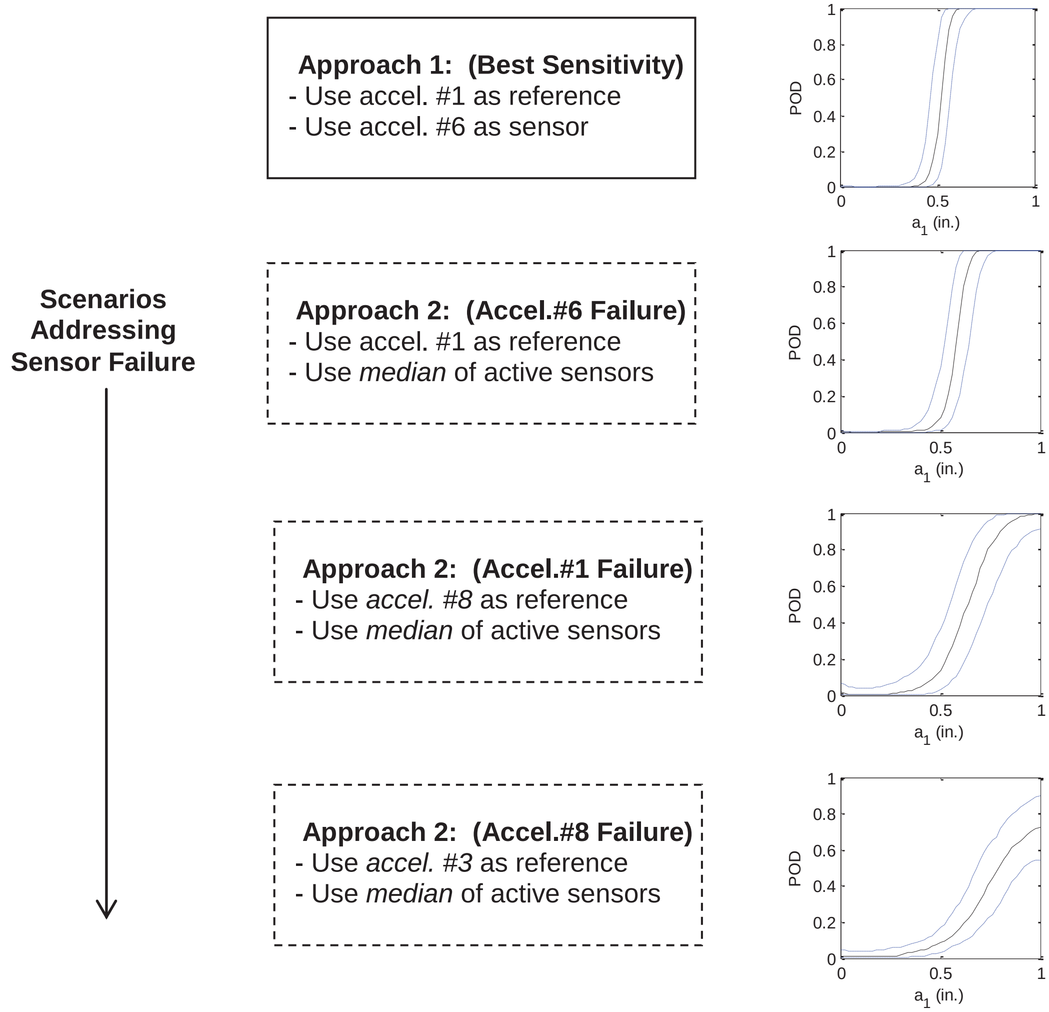

Figure 5. Sensor failure scenarios with matching changes in POD and false call rate ('flaw 3' model).

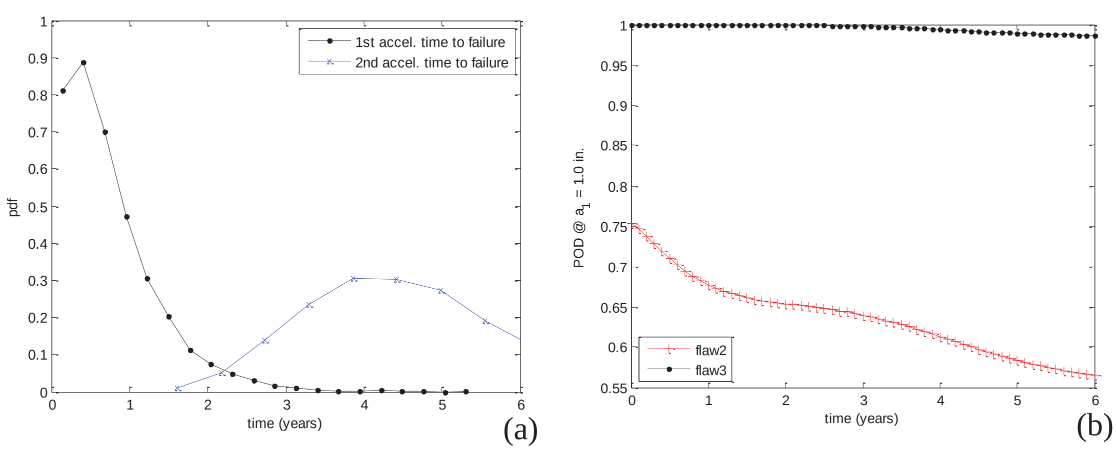

Figure 6. (a) Case study probability density functions for the time to failure for the first sensor and second sensor, (b) mean expected probability of detection (POD) at a flaw size of 1.0 in. with respect to time for all SHM systems found in the field.

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